

*** DESIGN TOOLS AND ISSUES OF SILICON MICROMACHINED (MEMS) DEVICES**

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ABSTRACT

This paper describes the design and design issues associated with silicon surface micromachined device design¹. Some of the tools described are adaptations of macro analysis tools. Design issues in the microdomain differ greatly from design issues encountered in the macrodomain. Microdomain forces caused by electrostatic attraction, surface tension, Van der Waals forces, and others can be more significant than inertia, friction, or gravity. Design and analysis tools developed for macrodomain devices are inadequate in most cases for microdomain devices. Microdomain specific design and analysis tools are being developed, but are still immature and lack adequate functionality. The fundamental design process for surface micromachined devices is significantly different than the design process employed in the design of macro sized devices.

In this paper, MEMS design will be discussed as well as the tools used to develop the designs and the issues relating fabrication processes to design. Design and analysis of MEMS devices is directly coupled to the silicon micromachining processes used to fabricate the devices. These processes introduce significant design limitations and must be well understood before designs can be successfully developed. In addition, some silicon micromachining fabrication processes facilitate the integration of silicon micromachines with microelectronics on-chip. For devices requiring on-chip electronics, the fabrication processes introduce additional design constraints that must be taken into account during design and analysis.

KEYWORDS

Micromachine; MEMS Design; Micro-Electro-Mechanical Systems

1. Introduction

MicroElectroMechanical Systems (MEMS) technology has tremendous promise and has generated a significant amount of interest in the academic, lab, government, and business sectors. This interest is primarily focused on the perceived potential performance and cost advantages associated with microscale devices fabricated using conventional silicon processing technology and equipment. While the market for micromachined devices is expected to reach between \$10 billion to \$14 billion dollars per year^{2,3} by the year 2000, the current and projected market is very segmented. Efficiently and profitably accessing the segmented MEMS markets will likely require significant design flexibility, integration between micromachines and microelectronics, well characterized processes, and a full suite of design, simulation, and analysis tools. In order to be profitable, fixed costs associated with developing and maintaining repeatable fabrication processes (equipment, facility, and other process development costs), and the

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fixed costs associated with designing, analyzing, and laying out micromachines and microelectronics (device development costs), must be shared by several or perhaps many different MEMS products. By amortizing the costs of developing multiple market segments or niches, the per-chip costs can be effectively minimized allowing the MEMS technology to penetrate a broad scope of market segments and applications.

2. Design Tools

Efficient MEMS development not only requires reliable and repeatable fabrication processes, but it also requires flexible and integrated design and analysis tools. Several commercial entities have developed design tools for MEMS, each with its unique set of strengths and weaknesses. Additionally, assorted non-MEMS design tools have been applied to design and analysis of MEMS according to the abilities and needs of MEMS designers.

3. Mask Layout Tools

The layer geometry (including layers of polycrystalline silicon, silicon dioxide, and silicon nitride) of each patterning step in the fabrication of MEMS devices is defined by a 2-D mask. Masks are fabricated from 2-D mask layout drawing files. Several different layout tools are used for this purpose. At Sandia, we have standardized on AutoCAD® R13 and R14. (An example of an AutoCAD® layout of a MEMS accelerometer is shown in Figure 1). AutoCAD® is a general purpose mechanical design and drafting software package that is widely used in the engineering community. Because of its widespread use, AutoCAD® has many interfaces and 3rd party software modules that makes it use viable in a variety of MEMS design applications.

Once mask levels have been defined within the layout tool, certain types of design errors are checked with design rule checking software. The design rule checking software checks such geometric features as minimum feature resolution, minimum spacing between adjacent elements, etch release hole spacing, etc. Design rule checking helps improve MEMS device yield by flagging geometric features that will likely result in process or design problems. Design rule checking helps MEMS designers avoid design mistakes that would jeopardize proper function of their MEMS device (such as not completely separating parts that move relative to each other) or adversely impact other designs on the same wafer (such as not anchoring parts that would float free from one design and mechanically interfere with operation of other designs).

4. Mechanical Finite Element Analysis and Visualization Software

Certain kinds of finite element analysis software can be applied to MEMS devices as long as a good understanding of device and microdomain physics are taken into account and scaling and unit conversion is performed correctly. In the MEMS domain, effects due to Van der Waals forces, capillary and surface tension effects, and electrostatic forces can easily exceed inertial, material deflection, and friction forces which usually dominate models of macrodomain devices.

At Sandia, one type of finite element analysis software that has been successfully applied to MEMS analysis is called ANSYS/AutoFEA®, and is compatible with AutoCAD® generated geometry. For the MEMS accelerometer design shown in Figures 1 and 2, the results of analysis using the ANSYS/AutoFEA® software predicted maximum deflection at 10 G's of 0.15 microns (for the open loop control case) and resonance at 4 kHz. Additionally, the design factor of safety exceeds 10 for the stress states calculated for a 10 G acceleration event.

With some of the MEMS-specific FEA software now becoming available, a MEMS designer can model and analyze a MEMS design with such capabilities as 3-D visualization (automatic construction of a 3-D model of the MEMS

device based on the composite of the 2-D mask definitions and the fabrication process description), automatic meshing of the MEMS model (designer defines boundary conditions and loads then the software automatically creates a finite element mesh of the 3-D model), solver analysis (full model analysis of characteristics such as structural mechanics, electrostatics, vibration, heat transfer, fluid flow, and coupled electro-mechanics), and simulation (iterative analysis used to formulate the sensitivity between device performance parameters and changes in design or operating parameters).

5. Standard Mechanical Components Libraries

Certain mechanical components can be used in a variety of applications, and so it makes sense to develop an infrastructure and means for creating a database of useful MEMS mechanical components that can be inserted into appropriate designs. For example, using the standard component library developed for a specific fabrication process, such as Sandia's SUMMiT process (Sandia Ultra-planar, Multi-level MEMS Technology), very sophisticated micromachines can be fabricated by coupling individual components together. In the pop-up mirror assembly shown in Figure 3, electrostatic comb drives are coupled to a drive a 50 μm diameter pinion gear meshed to a 10:1 speed reduction transmission. The transmission is coupled directly to a linear rack which drives the motion of the the hinged micromirror between 0 and 90 $^\circ$. The electrostatic comb drives, pinion gear, speed reduction transmission, linear rack, and pop-up mirror are each components available to SUMMiT process (a four-level polycrystalline silicon surface micromachine prototyping process) users through the standard components library.

Figure 1: AutoCAD® layout

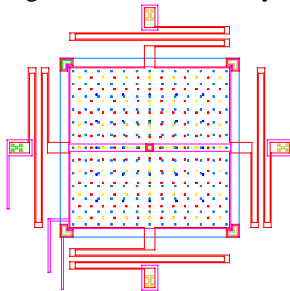


Figure 2. FEA of accelerometer

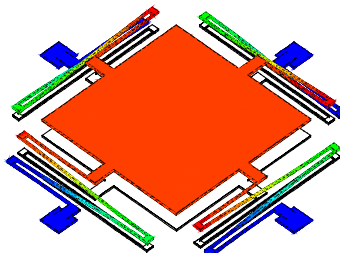
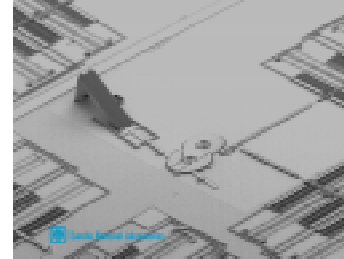


Figure 3. Pop-up mirror system



6. Accelerometer Design Example

Accelerometers are important sensors in a variety of applications ranging from air bag actuation and anti-skid braking to navigation and flight control. Design of a MEMS accelerometer was accomplished at Sandia using many of the design tools described in this paper and shown in Figure 1 and 2.

The accelerometer consists of a plate or proof mass suspended by four folded springs. Above and below the suspended proof mass are an upper and lower electrode, respectively. Each electrode acts as one electrode in a parallel plate capacitor, where the suspended proof mass, which at equilibrium is centered between the upper and lower electrodes, acts as the second parallel plate for both the upper and lower electrodes. Accelerations cause the suspended proof mass to be deflected towards the upper or lower electrode. This changes the capacitance between the upper electrode and the proof mass as well as the capacitance between the lower electrode and the proof mass. This change in capacitance is detected and a voltage is applied to the electrode that is sensing the proof mass moving away from it. This results in an electrostatic attraction force between the suspended plate mass and the electrode which keeps the proof mass centered between the upper and lower electrode. The voltage (or number of discrete voltage pulses) required to keep the proof mass centered is a measure of acceleration.

The spring suspension system as well as electrostatic electrodes can be seen in the AutoCAD® rendering of the accelerometer (Figure 1). Mechanical stops were also implemented at each corner and the center of the capacitive plate sensor to restrict lateral and vertical movement during shock or other high acceleration events.

Additionally, the accelerometer mechanical structure was designed to be controlled using a $\Sigma\Delta$ control system similar to those designed by Lemkin, et. al. at the University of California at Berkeley⁴.

The suspended proof mass is perforated by 144, $2\mu\text{m} \times 2\mu\text{m}$ etch-release holes (see Figure 1). The number and spacing of the etch-release holes (necessary for proper fabrication of the sensor element) results in a very low damping ratio (very high Q). The calculated (through analytical analysis) natural frequency of the sensor is 4,070 Hz which is very close to the resonant frequency of 3,898 Hz predicted using finite element analysis.

7. Conclusions

Design tools and infrastructure have been developed and adapted to support the fabrication of sophisticated silicon micromachined devices. This process has been used successfully by both internal and external MEMS designers in a wide variety of device applications. Using these design tools and process, it is possible to design and fabricate complex MEMS devices that work after only one design cycle⁵.

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